TUBULAR WELLS AND WELLS IN GENERAL,

AS A SOURCE OF

WATER SUPPLY FOR DOMESTIC PURPOSES.

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TUBULAR WELLS FOR DOMESTIC WATER SUPPLY.

The question of water supply for domestic use, is most commonly treated from the point of view of public water works for the general supply of cities, villages, or other dense populations, by pumps or by gravity flow from an elevated source, through appropriate conduits, mains and service pipes.

The magnitude of such public water works, the magnificence of some of them, and the utility of nearly all, draw attention to such constructions, and secure for them general recognition.

Requiring a high degree of special skill, such works are usually carried out under the supervision of competent engineers, who often give the public the advantage of their ripe experience, and enrich the literature of the engineering profession with contributions of great value. This state of things is not to be deprecated, but is rather to be highly commended. For populous and crowded places, some source of water supply extraneous to the places themselves must usually be very desirable and often imperative. Mischief is sometimes done by introducing a copious water supply in advance of adequate drainage, — the polluted streams of house drains poured into inadequate sewers and delusive cesspools, to poison the surrounding soil, and through the diffusion of dangerous, sometimes fatal effluvia, causing injury to the public health outweighing, perhaps, the advantages of pure and abundant water. A little extravagance — for the most

part harmless — is now and then indulged in through ostentation or defective judgment, in the erection of costly reservoirs and elegant pumping stations; but even these, once paid for, become objects of honest pride to the citizens, and would rarely be relinquished for a return of their cost many fold.

New works of this character will be constructed year by year in communities yet unsupplied; and in the great cities, systems more vast and more superb than any hitherto undertaken, will yet be accomplished. Boston, and the cities on the Merrimack (Lawrence, Lowell, Manchester), and, perhaps, other places, may some day be supplied with unfailing streams of uncontaminated water from Lake Winnipiseogee; New York and the intervening cities from Lake George, and San Francisco from Lake Tahoe. But when all is done, no less than at the present time, the great reliance of the rural population, including, of course, that large and increasing portion of the population of cities which passes a part of the year in the country, must be, as it now is, upon wells.

In almost all places fitted for human habitation, water is to be obtained at a greater or less depth below the surface of the ground. Wherever found, it has fallen from the clouds, has sunk into the ground through permeable soil, and having reached some impermeable stratum, such as impenetrable clay or hard, unbroken rock, is creeping with stealthy flow, through the interstices of the soil to lower levels, on its way, by some path more or less obstructed, to the sea.

Wherever precipitation exceeds evaporation, it is impossible that there should ever be a cavity below the sea level, unfilled with water, unless artificially emptied; and even in localities where evaporation from the surface greatly exceeds precipitation, the copious showers of the rainy season, deeply sunk in the permeable soil, and protected from rapid evaporation by the dry earth above their surface, although constantly flowing seaward, maintain an unfailing supply for human needs within easy reach. In parts of California, where rain seldom falls between March and December,

where a temperature of 96° to 104° F. by day, and 70° to 75° by night prevails for almost half the year, with drying winds and cloudless skies, the water soon drains and dries away from the natural drainage channels, and sinks down in the adjacent soil below the level of their beds, leaving at most but here and there a pool in their deeper portions, stagnant, but for the almost imperceptible underground flow.

These channels, often a hundred feet, sometimes several hundred feet in width, and twenty to fifty feet deep, called "sloughs," (*sloos*), are skirted by bushes, and covered in summer with rank vegetation. But the rainfall of the rainy season, re-enforced by that which drains down from the numerous mountain ranges into the broad valleys, fills the ground up to a level higher than the beds of these sloughs, along which streams then flow as in ordinary rivers, and the sloughs assume the character of a complete system of natural drainage. Flowing along these channels with less obstruction than through the interstices of the soil, the water in these streams is lower than the surface of the adjacent ground water, which therefore drains into them, yet continues its obstructed flow by their side at a higher level. In the great valley of the Sacramento the general slope of the ground is about four feet in a mile, and the water in the ground preserves about the same slope, and flows for miles in width beneath the surface of the ground in the same general direction that the river pursues between its banks, but with greatly reduced velocity, and at a level higher in proportion to its remoteness from the open channel, towards which it also tends. Wherever the level of this sheet of underground water is reached, an unfailing supply is secured.

The ordinary method of getting at this water, is by boring a hole with a pod-auger, and dropping a tube of 1½-inch gas-pipe into it — the work of two men for half a day, when the depth does not exceed fifty feet. But open wells are also made with equal success, though at greater cost; and deeper wells are sometimes sunk, passing through one and occasionally through two impervious beds of clay to different

strata of water-bearing sand or gravel, all filled with water of substantially the same character and temperature, derived from the same source — the rains of winter, all flowing in the same direction to seek the same outlet, and all rising to the same height in the tubular wells — allowance made for difference of location.

In such cases the problem of well-sinking for water-supply is extremely simple. Other conditions, often of great complexity exist in parts of California. I have spoken only of what has fallen within my own observation, in the great valleys of the Sacramento and American rivers. In most parts of the Northern, Eastern and Middle States, in which the softened materials of decomposed granite, conglomerate and other hard rocks have been disturbed by the action of vast accumulations of ice, and swept into moraines and beds of glacial drift, the conditions under which water is found below the surface of the earth are extremely various.

Sometimes — the cases are exceptional, but not very rare — a permeable bed of sand or gravel not far from level, extends in all directions to natural drainage channels — brooks, ponds, rivers, or the ocean — affording, when not sealed by frost, free reception and secure storage for a large part of the rain-fall. Some water runs directly off from the surface into the drainage channels, during violent showers and when the ground is frozen; some, falling in small quantities upon warm, dry ground, is soon reëvaporated; but in large part, rain-fall upon such homogeneous, permeable soil, unfrozen, sinks quietly down upon the surface of the water already filling the pores and interstices of the ground up to a certain level. The aggregate volume of these interstices is nearly the same in all soils. Sand, whether coarse or fine, and gravel of whatever size, when sifted out so as to consist of grains or pebbles of nearly uniform size, approximately spherical in form, and when well compacted, have about 60 per cent. of their volume occupied by solid materials, and about 40 per cent. by cavities which must, in all natural conditions, be filled with either air or water. When grains and pebbles of varying dimensions are mixed together, as is the

case in nearly all natural sands and gravels, the finer portions occupy to a certain extent the interstices of the coarser portions, and the proportions become about 63 per cent. solid to 37 per cent. vacant, or filled with either air or water. These proportions hold good for very fine quicksands, appearing, when taken from their beds, like clay, or cream, yet when dried exhibiting under the microscope the character of true sand, and revealing — in New England — their origin in triturated granite, the quartz and felspar reduced to shining transparent and nacreous pebbles, and the mica comminuted to an impalpable powder. I have discerned this character in quicksand where the grains were less than $\frac{1}{1000}$ of an inch in diameter.

Clays, even when nearly impervious to water — forbidding its transmission although permitting its absorption — really possess as much open space, in the aggregate, as sands and gravels, as is proved by their specific gravity, which is substantially the same for all three; while the solid materials of all are, again, of substantially equal specific gravity; but in many clays the interstices between the extremely minute solid particles are too small to admit the passage of water through them. In very fine quicksand, water, it is true, freely penetrates the pores, but is drawn by surface attraction between contiguous surfaces of the solid particles, forcing these particles apart, and resulting in an enlargement of volume when saturated, and a corresponding shrinkage in drying, the measure of which varies with the texture of the sand. I have found it about 4 per cent. in a rather coarse and very pure granitic quicksand, and 8 per cent. in a finer sand of similar character. It is this which gives to quicksands their fluid or *quasi* fluid character.

But while the actual storage capacity of all porous soils is substantially the same, and in all cases rather over than under 40 per cent., considering the compressibility of all — or nearly all — natural earth, the quantity which will drain out, and is therefore available for use, varies extremely with varying size of grains, particles or pebbles. From a rather coarse sand, 47 per cent. of which would not pass through a sieve with open meshes 0.053 in. diameter, and only 16 per

cent. through 0.024 in. meshes,* a quantity of water was pumped out equal in volume to 22.3 per cent. of the total volume of the saturated sand, although the open space was, in the aggregate, 37 per cent. The balance, 14.7 per cent., equal to 40 per cent. of the contained water, was required to wet the surface of the sand grains. This sand, it is true, was well compacted, and the open space was less than in natural sand beds of equal fineness. In coarser beds, the yield is much more; in finer beds, much less. It is probable that in most beds so freely permeable as to be considered water-bearing strata, from 10 to 30 per cent. of the space may be used as storage capacity, the average being, rudely, 20 per cent. This accords with the results of a considerable number of observations of rain-fall and corresponding rise of the surface of ground-water.

An inch of rain, sinking quickly down in level, moist,

* *Physical analysis of the sand above mentioned.*

No. of Grade.	Nominal number of meshes per linear inch.	Diameter of wire: by measurement. In.	Mean size of mesh passed through, including wire. In.	Mean size of open mesh passed through each way. In.	Weight in grains: 7,000 grains to one pound avoirdupois. Grains.	Ratio of each grade to the total weight. Per ct.	Specific gravity of solid particles. Sp. gr.	Ratio of full space to total space. Per ct.	Ratio of empty space to total space. Per ct.
1	50 pebbles	–	–	–	394	4.2	2.61	–	–
2	–10	–	–	–	983	10.6	2.61	57.0	43.0
3	10–12*a*	.0181	.1026	.0845	362	3.9	2.61	–	–
4	12–16	.0125	.0870	.0745	1,606	17.3	2 64	60.6	39.4
5	16–20	.0098	.0625	.0527	1,017	10.9	2.63	59 7	40 3
6	20–30	.0096	.0534	.0438	3,409	36.7	2.62	59.7	40.3
7	30–40	.0113*b*	.0352	.0239	1,021	11.0	2.61	60.3	39.7
8	40-50	.0095	.0260	.0165	190	2.0	2.61	57.7	42 3
9	50-60	.0075	.0200	.0125	47	.5	–	–	–
10	60-70	.0067	.0188	.0121	63	.7	–	–	–
11	70-	.0060	.0159	.0099	209	2.2	–	–	–
–	–	–	–	–	9,301	100.0	2 62	59.75	40.25

a Through 10 x 10; *not* through 12 x 12. *b* Change from iron to brass wire.

Mean specific gravity of the porous mass, compressed, dry, $= 2.62 \times .5975 = 1.57$.

Weight of 1 cubic foot, compressed, dry, $62.3 \times 1.57 = 97.8$ lbs.

Weight of water which one cubic foot will contain, $62.3 \times .4025 = 25.1$ lbs.

Weight of 1 cubic foot saturated with water, $97.8 + 25.1 = 122.9$ lbs.

In natural sand, all sizes mixed together, the finer grains partially filling the interstices of the coarser sand, compressed, dry, the full space = 63 per cent.; empty space, = 37 per cent.

Weight of 1 cubic foot, dry, 102.80 lbs.; wet, 125.85 lbs.

This sand appears to be composed chiefly, if not entirely, of disintegrated granite, the quartz and felspar, and some hornblende, in palpable and distinguishable grains, and the mica in an impalpable powder

permeable earth, will raise the surface of the water underground about 5 inches; will by so much increase the steepness of the underground water-slope towards the open drainage-channels, and in a certain degree, determined by the circumstances of each case, accelerate the underground flow.

Each subsequent shower, so long as the rain-fall exceeds the annual average, still further increases the slope, until a maximum is reached, at a level, varying with the season, from which it subsides during the drier portion of the year, as the water seeps away, to the lowest stage for the season. For a distance of eighty miles along the southerly shore of Long Island, N. Y., and for a distance of from three to fifteen miles inland, the surface of the ground is not far from level, and the texture of the soil is so nearly homogeneous that the underground water declines towards the ocean with a slope almost uniform at any particular time, but varying with the rain-fall, between the limits of two and eight feet in a mile. Streams flowing down from the interior a mile or two apart, have a surface slope of from two to eight feet per mile.

Roads, at similar intervals, are bordered by farm-houses, each supplied with water by a well, in all of which the height of the water varies with the season, as I have described, but always in strict mutual relation, so that the height of undisturbed water in one well being ascertained, the height in all neighboring wells may be known by comparison. Many cases of this kind have come within my own observation, and many more have been brought to my notice by engineers of wide experience, some of them offering very interesting peculiarities, the consideration of which would lead us too far, but all presenting the same underground flow induced by a surface slope.

Under conditions such as we are now considering, the construction of wells is a simple process. The very first one in any such locality will probably offer few unexpected difficulties, and no formidable ones; and after a few are made, others may be as accurately estimated, both as to the time and cost, as roads or ditches. The slope of the underground water may be determined with reasonable precision, and the variations of surface-level will reveal the probable

depth of the well. A dry period of the year being preferably chosen, it is only necessary to sink a pit to the water, and as much lower as may be conveniently practicable, and to sustain the surrounding earth by "steening" — the word is technically accurate — of stone or brick. For a certain height at the upper end, the steening should be surrounded with good clay,* well puddled, and raised a little above the surrounding earth; but quite at the surface of the ground and for four or five feet below, there should be a foot in thickness of sand between the steening and the clay (which may judiciously be enlarged in diameter at the top to fifteen or twenty feet), to avoid danger of disturbance by frost. A well so made, is a "pit-well," and the central cavity of its lining, or steening, is the "well-pit." To the unreflecting, this well-pit may seem to be the well itself; but if a well be indeed a source of water-supply, we must give the word a wider meaning. Left undisturbed, the water within the well-pit will rise to a level with the ground-water around it. This statement needs a little qualification. Strictly speaking, the surface of the ground-water, in the conditions we are considering, is never level — nearer level after long drought than when recent and heavy rains have added to its volume — but still always sloping towards its natural drainage outlet, from two to eight feet in a mile, equal to from $\frac{1}{70}$ to $\frac{1}{18}$ of an inch in the width of a three feet well.

By one-half these quantities, then, the water in the well-pit will stand below the level of the ground-water at the up-stream side, and above it at the down-stream side, using the terms "up-stream" and "down-stream" with sole reference to the direction of the under-ground flow. Small as these quantities are, especially the former — for $\frac{1}{18}$, or even $\frac{1}{36}$ of an inch is a very appreciable fraction — such a slope as they indicate is quite sufficient to give rise to a perceptible flow through the interstices of porous natural earth, and is certainly sufficient to cause water to trickle into the well-pit from the soil on the up-stream side, and to filter out into the soil on the down-stream side.

* Clay for puddling should be mixed with gravel, in proportions to be determined in each case by experiment.

Left to itself, the water of such a well will be slowly but constantly renewed, almost as if it were unimpeded by the sand-grains or gravel-stones of its native bed. Left still undisturbed, not much water will flow into the well-pit from a lateral direction, and none from its down-stream side. The water it will receive will come to it in a narrow stream, of width little greater than its own diameter.

Whatever soluble matters, derived from any polluting source, may come to it, must come from within the borders of that narrow stream; all else will pass by it, or flow away from it. But the instant water is drawn out of the well-pit, all this is changed. A bucket or two drawn out, may lower the surface of the free water in the well-pit an inch; sufficient, if long enough continued, to produce a level and arrest the flow away from the well, on the down-stream side, for a distance of two hundred and twenty feet at the flattest, or fifty-five at the steepest slope; and to produce a current *towards* the well from the down-stream side equal to the previous flow away from it for half these distances — one hundred and ten feet to twenty-eight feet. Taking for illustration the latter figures; that is, assuming the slope of the underground water surface to be eight feet in a mile, equal to one inch in fifty-five feet, and that water is steadily drawn out of the well so as to keep the surface of water within the well-pit one inch below the level at which it would stand if undisturbed, we shall have the current reversed and turned toward the well on the down-stream side for about twenty-eight feet; quickened in its flow toward the well, from the up-stream side, for a much greater distance, and diverted toward the well in a lateral direction for a distance of about fifty-five feet each way. Now, all the water flowing through the interstices of the soil in a stream about one hundred and ten feet wide will be diverted from its down-stream course, and concentrated at the well-pit, by the crater or cavity one inch deep in the middle and extending out fifty-five feet each way, *across* which it cannot flow by gravity — its sole impelling force. All the pollutions of the surface, from barn-yards, and the refuse of human habitations, and manured fields, so far as soluble matters from these sources are carried down by the rains to and into the ground water, in this

stream tributary to our well, one hundred and ten feet wide when its surface is steadily depressed one inch, and for a great and indefinite distance up stream, finds its way into the well-pit.

If the rate of pumping is increased, a lower level maintained, and a steeper slope produced, the tributary area will be proportionately enlarged, and the actual quantity of polluted water will be augmented, although not necessarily in greater proportion than the increased quantity of water, which, therefore, will not necessarily be any more impure. If largely and constantly drawn upon, so as to maintain a level two, three or four feet below the natural level of undisturbed water at that place and time, a slope will be given to the underground water, from all sides, towards the well-pit, extending hundreds of feet in radius all around, and bringing to it whatever soluble impurities may have been received by infiltration within this area. Barnyards, pigsties, cesspools, privy-vaults, sink drains, all will contribute whatever is soluble to the mixture.

Fortunately such a state of things can rarely attend the ordinary use of a well for the domestic supply of a single family, or even two or three families. A quantity no greater than three hundred or four hundred gallons per day distributed over the hours of daylight, would rarely depress the surface enough to cause a slope towards the well-pit from a greater radial distance than one hundred feet. If, therefore, care be taken to avoid all sources of contamination for a great distance in the direction from which water flows naturally, and to keep all such sources of danger one hundred feet or more away in all other directions, reasonable security may be looked for, provided the water within the well-pit is never drawn down more than a few inches below its natural level — the level to which a few hours of rest will restore it.

Several considerations of a general nature, applicable, *mutatis mutandis*, to almost all wells, are suggested by these conditions.

First: The supply of water to be obtained from a well is almost independent of the diameter of the well-pit. As a mere reservoir of open water to be immediately drawn upon,

the value of the well-pit is in direct proportion to its cubic capacity below the water level; but as a source of continuous supply, it is to be measured almost wholly by the extent of territory from which water can be induced to flow towards the depressed surface of the water where drawn out, in connection with the porosity or retentiveness of the soil.

Second: In any given locality, two or more wells will yield no more water than one, since one, if freely and continuously drawn from, will lower the water in others near it; but if one hundred feet or more apart such mutual disturbance should not usually be felt in ordinary domestic use by single families.

Third: So long as water can be drawn out without disturbing the earth and sediment at the bottom, the yield can be increased by drawing out water freely, and thereby maintaining a lowered surface in the well-pit, and a wider area of convergent flow; and this quite irrespective of the relative height of the natural water level at the time.

Fourth: It is unimportant as to the quantity, how such depressed surface is maintained — whether by a bucket, or by a pump, or by one kind of pump or another; — by hand-power, horse-power, steam or windmill; a given depression of surface, resulting in a determinate slope, under established conditions, will produce a certain flow of water by its own gravity, notwithstanding the interstitial friction of the soil; and no human instrumentality exerted at the well can influence this flow in any other manner than by lowering or raising the water level in the well-pit, and thereby increasing or diminishing the slope.

Fifth: The danger of pollution — malice apart, and wind-borne dust left out of consideration — is not at the open mouth of the well, but on the permeable surface within the tributary area, a circular area of one hundred feet radius or more, and in the case of wells subject to constant and heavy draught, several hundred feet.

An open well consists of three essential parts: *First*, the shaft, leading down to the water; *second*, the well-pit extending below the surface of the water; and *third*, the surrounding porous earth, out of which water will flow by gravity alone into the well-pit whenever the surface within the

latter is drawn down below the outside level, with a velocity due to the slope of the surface, in the existing conditions of interstitial friction.

This would still be true even if the surrounding water were part of a vast subterranean lake open to and continuous with the well-pit; only in such case the slope would be insensible because the friction would be only the fluid friction of open water, which is insensible to ordinary methods of observation; but in all natural soils, even the most porous, the slope necessary to produce rapid flow is very easily detected, observed and measured.

Of these three parts, the first and second must usually be provided by human agency. The third must be supplied by nature and replenished by the rains of heaven. For almost all purposes, a simple pipe or tube, sunk into the earth a few feet below the surface of the ground-water at the lowest stage from which it is to be drawn, will constitute a perfect equivalent of the open well-shaft; and the cavity which will soon be formed around the lower end of such a pipe by drawing out with the water the sand and finer pebbles mixed in the soil with coarser material, will become a substitute for a well-pit. If the water be drawn out by means of a pump attached directly to the pipe at its upper end, this sand will be found troublesome and injurious in the pump, and on that account it is customary to furnish the lower end of the pipe with a strainer of some kind, to intercept the gravel and the coarser sand. When an efficient strainer is used, which really excludes from the pipe all but the finest sand-grains, the formation of a cavity around the lower end of the pipe is greatly impeded, and the "well-pit" is reduced to a rudimental form — all that is left of it being that space within the pipe below the water level, which would be occupied by the same pipe if inserted as the suction-pipe of a pump in an open well; and even this so altered in character from a true well-pit as to be irrecognizable, inasmuch as *within* the pipe a portion of the normal weight of the atmosphere may be lifted off by the pump-piston, and some degree of "vacuum," so called, may be formed, while *without*, upon the water surface outside of the pump-pipe, the full weight of the atmosphere must always rest as in an open well-pit.

The pump, therefore, may be made to facilitate the flow of water from the outside to the inside of the pipe, provided water is already actually present at the outside, so as to wet the exterior surface and exclude air, and provided, also, other water is present to push it in and to take its place; and so on, in a continuous stream to the surface on which the atmosphere rests, whether that surface be open, as in an uncovered pit-well, or covered over with a platform, or with earth, which in all ordinary natural conditions is freely permeable to air at low velocities with extremely moderate pressures. The entrance of water into the pump-pipe from without, is necessarily attended with a depression of the water-surface immediately around the pipe; and that by a flow from a little wider circle and consequent lowering *there*, and so the influence is propagated in ever widening circles. But if the pumping is continuous, the flow must be continuous; and a uniform quantity of water continuously flowing from wider to narrower circles, must flow with a constantly increasing velocity. Now such acceleration can be produced by nothing but a constantly increasing steepness of slope.

This acceleration of water in porous soil in approaching a central depression, must not be confounded with the acceleration of falling bodies *in vacuo*, or even in the air, which offers comparatively little resistance, except, indeed, to bodies of very low specific gravity. Acceleration of water in the soil, is much less than in open air, and the velocity varies more nearly as the head, than as the square root of the head. But the curve of the surface in vertical, radial section, is convex upward, and grows continually steeper from the extreme limits of the well's influence, as the well is approached. The limit of the influence of a depressed well surface, is the point at which the lessening slope becomes too small to produce sensible flow through the interstices of the soil, and will depend, in every case, on the the amount of depression of water surface at the well, — the moving force, — and the interstitial friction of the soil — the impeding force.

It necessarily follows that the mode of putting down the pipe of a tubular well, whether by boring, or driving, or digging, or by washing out the earth from within by a current of water, is without influence upon the quantity of

water obtainable at any given time and place. The condition of the earth around the pipe is equally without influence in this respect, whether it be in close contact, or separated by a wide or narrow space. Substantially the same quantity of water will be obtainable, whether the pipe be forcibly driven down all the way or inserted in a hole bored part way down, large enough to receive it freely, and driven the rest of the way, or dropped loosely into a larger pipe put down the whole distance, forming a lining, open at its lower end, but otherwise impermeable, or put as an ordinary pump-pipe into an ordinary open well. In any and in all these cases, the pump, if of suitable size, can produce by drawing out a given quantity of water in a unit of time, a certain depression of surface around the pump-pipe, substantially the same in all cases with substantially the same expenditure of force; and a convergent, radial, interstitial flow, substantially the same in all cases, will result as a secondary effect of the pumping, through the depression and attending slope.

Substantially the same: not exactly. On reaching the circumference of an open well, the water will flow thence up to wetting contact with the pump-pipe without sensible slope; but with earth filling all this space, it must have a very considerable slope to maintain its velocity, and, therefore, the tubular well surrounded by earth, whether in close contact with the pipe or not, will always require a little greater depression of the water surface, and a little greater outlay of force to obtain an equal flow — an equal yield — than will a pump in an ordinary open well.

This difference, although quite observable, is not very important, and for most purposes, and in all ordinary cases, a tubular well and an open well may be considered as substantially equivalent. The choice between them is practically limited to a question of cost and convenience. These considerations will vary with the varying character of the soil and other natural conditions, on the one hand, and with the facilities which the given locality affords for obtaining the requisite tools, materials and skill for constructing the two kinds of well, respectively. If well diggers of experience, skill, and responsibility are at hand, and ready to make an open well for a reasonable price, there can be no sufficient

reason for incurring either extra trouble or extra expense to obtain a tubular well, and a similar remark is no less true in an opposite sense, under reversed conditions.

I have considered, above, it will have been observed, the conditions arising when the pump was attached directly to the upper end of the suction pipe, necessitating a strainer at the lower end of the suction pipe, to exclude from the pump entrained sand and gravel, which would injure the pump, and soon destroy it, if, indeed, they did not altogether stop its working by excessive friction. It is often better to set the pump at a little distance from the pipe, and connect it with the upper end of the pipe by a short section of horizontal pipe, with an enlarged chamber, provided with suitable deflectors, screens, and openings for removing sand and other solid materials drawn up with the water. Such an apparatus, called a "sand-chamber," is well known among the makers of tubular wells. Being above the surface of the ground, it is always accessible for clearing out and for repairs, and there need be nothing below the ground at all liable to disarrangement or rapid deterioration. By the use of such a sand-chamber, a considerable space around the lower end of the pipe, may be emptied of its finer material, and a resulting cavity may be formed, partly filled with stones too large to be pumped out, but in all essential respects equivalent to an open well-pit, considerably improving the operation of the well.

Among the various competing systems of construction, some may offer an advantage in one locality, but be surpassed in another locality by another system; but the considerations relevant to this question of comparative availibility are such as relate exclusively to the cost and convenience of construction; all are substantially alike when once completed. An excellent method is to first force a pipe into the ground as far as it can be driven without injurious violence, and then to remove the soil from the inside by means of a stream of water forced down through a smaller pipe. If the suction pipe is one and a half-inch, one and three-quarter-inch, or two-inch gas pipe, — all very suitable sizes, — the auxiliary pipe may be of three-quarter-inch gas pipe. Its lower end should have welded into it a point of solid steel of square or

triangular section, and several holes one-quarter-inch or a little more in diameter should be drilled a short distance above the solid point, to let out the water. Upon the upper end of this pipe, is to be screwed a common three-quarter-inch gas pipe T, into which two short pieces of three-quarter-inch pipe — each six or seven inches long — are to be screwed, forming a transverse handle, resembling an auger-handle, one end of which is to be stopped with a cap, or coupling and plug, while the other end is left open to connect with a suitable hose to convey water into the pipe, from a hydrant or from a force-pump provided for the purpose. The steel point, forced into the earth within the pipe and turned by the handles, will loosen the soil, and facilitate its removal by the stream of water forced out of the holes near the lower end of the pipe.

This loosening and washing out process may be carried below the end of the suction pipe at the time, to a depth which will depend upon the kind of soil encountered, and this will form a cavity somewhat larger than the outside of the suction pipe, which may then be very easily driven further into the ground. In this way it is not difficult or expensive to put down suction pipes of the size I have mentioned, in ordinary sands, gravels, and clays, where no bowlders or ledges of hard rock are encountered, to a depth of more than one hundred feet.

It is hardly necessary to say that if the water sought is surface water, that is, water that has settled down into the soil from the surface on which it fell, within the adjacent natural drainage channels, such pipes as these we are now dealing with, one and a half-inch to two-inch gas pipes, cannot be sunk, advantageously, more than about thirty feet, — thirty-three or thirty-four feet at the most. Too small to admit of the insertion of a practicable pump, such tubes can only be used as the suction pipes of pumps connected with them at their upper end, either directly in continuation of them, or indirectly by means of a horizontal pipe, with or without an intervening sand-chamber.

If, as is often the case, an abundant supply of water, really surface water, in soil permeable all the way down from the top of the ground — may be reached at a depth of thirty-five,

fifty, or sixty feet below the surface, a pipe of three-inch, three and a half-inch or four-inch gas pipe may be put down in the manner I have described, or in any other convenient manner, to a suitable depth below the surface of the underground water, — five or six feet below, — and after all the earth has been removed from within the pipe, together with as much as may be convenient of the finer material around its lower end, a pump-barrel, with its foot-valve or "sucker," its movable valve, or "bucket," and its suction pipe, may be inserted in the larger pipe, as in an open well dug and stoned in the usual manner.

Of course, the movable valve, or "bucket," at its highest position when in operation, must not be more than about thirty feet higher than the lowest level to which water may be depressed outside of the suction pipe by the act of pumping, and this at the lowest stage of the ground water; and it will be more convenient not to let it exceed twenty-five feet. In case the height to be lifted by "suction" is likely to be at times as much as twenty-eight to thirty feet, it will be well to put a supplementary valve — a true "foot-valve" — near the lower end of the suction pipe, as an additional safeguard against losing the water by leakage of the valves and bucket-packing. In many cases — perhaps in most cases — it will be desirable to provide the lower end of such a suction pipe with a fine strainer, of sufficient area to keep out sand without seriously obstructing the inflow of water, since in the case we are now considering an intermediate sand-chamber is not available.

So far as procuring a supply of water is concerned, it is quite immaterial whether the larger pipe, constituting a well-curb, be left in place after the pump with its suction pipe has been inserted to the proper depth, or drawn out, leaving the well unsupported to cave in around the pump and pipe, or not, according to circumstances.

For convenience of repairs when the bucket and valves become worn, the outer pipe is desirable; but in some cases it may be about as well to make a simple hole in the ground, without lining of any sort, and to put the pump and suction-pipe down into the hole. Such a construction was patented in England in the year 1823, by John Goode, a very distin-

guished inventor of machinery for constructing artesian wells, and also distinguished as a constructor of artesian wells, and of wells in superficial strata.

Goode's method was to make a hole of suitable size to the required depth, and "to force a pump-barrel with bucket and sucker down the hole, until the sucking-pipe entered the water;" and this method is perfectly available to-day. In most water-bearing strata, an efficient strainer will be required at the lower end of the suction-pipe. There are some existing patents, which may be valid, relating to methods of construction, and some care will be required to obtain a license from duly authorized persons; but the just measure of the license fee for the use of any such patent, is the saving effected by it in the construction of the well, and in no case can the cost of a tubular well, license fee included, justly exceed the mere cost by any one of several available unpatented methods, or methods on which, as in the case of Goode, the patent has expired, and the invention has become public property. Litigation now pending will probably settle before very long some questions relating to patents concerning which it may not be proper to say more in this place.

It will have been observed that so far we have had our attention directed exclusively to surface wells, in strata everywhere within their influence freely permeable to air and water, and substantially homogeneous, at all events in lateral extension, if of various superimposed strata. Such conditions being simple, are most favorable for the study of general principles. But although common enough, such conditions are far from universal. It not infrequently happens that surface water, in permeable strata, exists in extremely variable quantity and under very diverse conditions, in places only a short distance apart. In directing and superintending the construction of twenty or thirty open wells, all within the range of a mile or two, I have encountered many diverse conditions. Sometimes the quantity of water flowing into the well-pit gradually increased with the depth after it was first met, until it became unmanageable with the means available for keeping it out, and it was, therefore, necessary to stop where we were, and to stone up

and complete the well. Sometimes, not far from such a well, water would be found in a retentive stratum of fine material, out of which it would ooze slowly, with no very sensible increase in quantity even after the well-pit had been carried to a depth of ten feet or more below the surface of the ground-water; yet by slow and constant infiltration through a large area, when the surface was drawn down, yielding an adequate supply. Again, at no great distance, after digging several feet in earth substantially dry, a vein of water running freely under ground, almost as in a rivulet upon the surface, flowed into our excavation and ran away at the same level, requiring but a slight depression to dip out of, to give a plentiful water supply continually renewed.

In this latter case, and in similar cases, some original difference in the character of the soil had long ago caused a more rapid flow through some porous streak, and the current had gradually worn away its channel, partly by mechanical erosion, and partly, perhaps, by chemical solution, and so formed an underground stream, with tributaries flowing into it, hurrying to an outlet as a spring, either in a valley or side-hill, or in the bed of a river or pond. Of course in the vicinity of such a hidden rivulet the water would be mostly drained into it, and the adjoining earth must be nearly dry. Such a stream in fact produces naturally the effect I have described in connection with the surface of water in a well-pit artificially lowered — water flows out of the surrounding soil into it by gravity, because it is lower than the surrounding water surface would otherwise be. Sometimes in circumstances differing slightly from those last described, the water of such an underground rivulet is, at the point where the well penetrates to it, locally depressed by some fold of a stratum nearly or quite impermeable, and finds an outlet at a higher level. In such case, when water is reached, it flows in rapidly and fills the excavation to a depth corresponding to the height of the natural outlet. The surface of water in the well, when once it has come to rest, is the normal height of the underground water at such time and place, from which is to be reckoned the depression produced by pumping, which will result in underground flow, radially, towards the well. These last conditions approach closely to the condi-

tions necessary to the formation of artesian wells, and indeed sometimes shade into them by almost insensible degrees. The loose and perplexing use of the high sounding name, "Artesian Wells," for mere tubular wells — driven or otherwise — in surface strata, is to be discountenanced. Artesian wells, properly so called, can be made only where water, derived from an elevated source, often very remote, and always outside of the natural drainage channels directly about the site of such wells, is locally depressed in its path to some natural outlet, and confined by impervious over-lying strata below, sometimes far below, the level to which it would rise if not so confined. The accompanying section of the London basin, fig. I.,* so clearly indicates the conditions essential to the formation of artesian wells, that little explanation will be required. Rainfall upon the chalk stratum at its exposed margins, about Dunstable and St. Albans on the one side, and about Knockholt on the other side, sinks into the depressed portions of the same stratum, confined between the Gault clay below and the plastic clay and the London clay above, having its lowest natural drainage outlet at the point indicated by the letter C. The wells which are seen to be carried down to and into this chalk stratum at the points marked respectively D, E, F, G, H, and I, and at the Model Prison between E and F, all being so constructed as to admit water only at the lower end, are filled with water up to the level of the line A B, — the level of the lowest natural outlet, C, — unless their top be lower than said level. But, when, as at G and H, they are sunk in ground the surface of which is below the level line A B, the water will flow out above the surface of the ground. When it does not flow in this manner, it must be raised by pumping, which produces a relative depression in and immediately around the well, and as a secondary effect by means of such depression, a convergent flow towards the well. Here, as elsewhere, the weight of the atmosphere resting on the surface of the underground water at the exposed margins of the chalk, is equivalent to about thirty to

* Copied from plate XLVI., vol. V, professional papers of the Corps of Royal Engineers, published by John Weale, London, 1842, and described on pp. 267-268, of said volume.

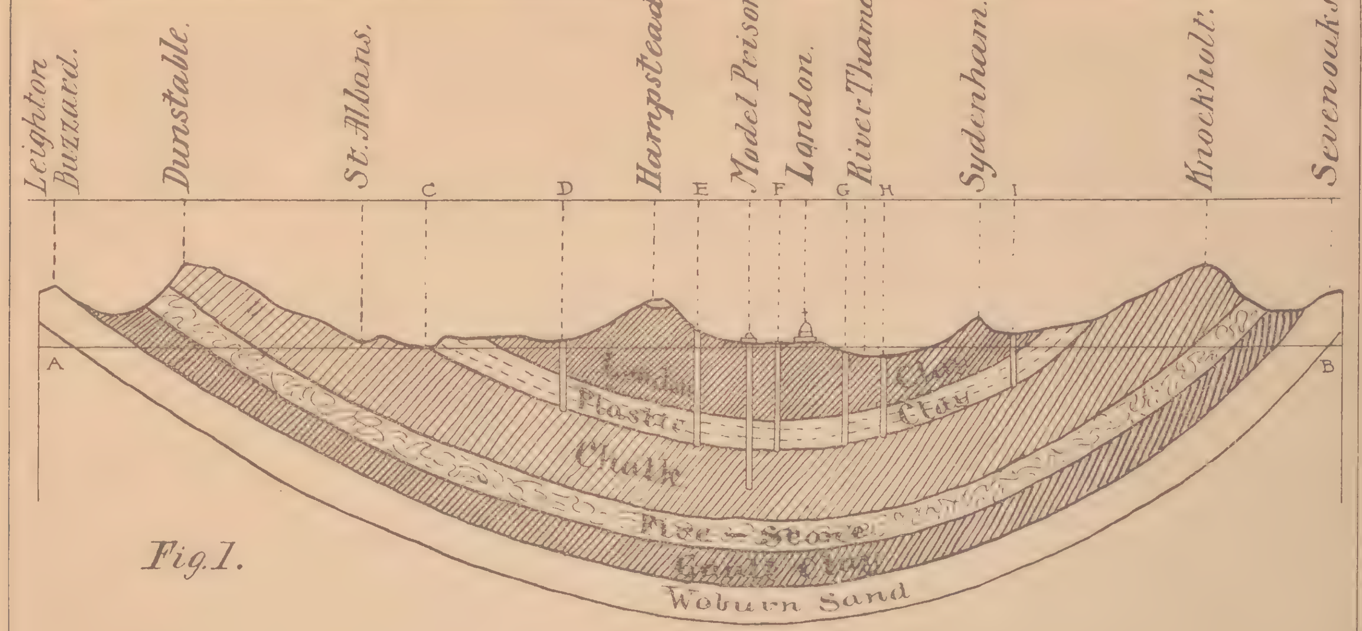


Fig. 1.

Section showing the Cause of the Rise of Water in Artesian Wells in the Basin of London.

thirty-three feet of water, and the removal of any part of this weight from the water surface within a pump, results in a differential atmospheric weight, to be added, in the form of an equivalent water column, to the surface depression produced in the well by pumping. The sum, will be the motive force to overcome interstitial friction and to concentrate water at the well.

Such wells are very numerous in the London Basin, and their number is constantly increasing, and as a consequence the general level of water is depressed year by year, as much, it is said, as two feet *per annum*. Yet so vast is the reservoir formed by the immense chalk deposit, that no apprehensions are felt as to the permanence of the supply.* This interesting set of conditions which makes possible the construction of artesian wells, can rarely, if ever, have any direct application to the construction of driven wells, or ordinary tubular wells. Sometimes a shallow pond or pool, supplied by no turbid streams, and protected by groves or forests from dust, save that which is never absent from the purest air, has gathered through long periods of time from the winds that swept over its surface a slowly formed deposit so fine as to form a tenacious, impermeable bed, perhaps indurated by calcareous or ferruginous cement into "hard-pan," perhaps retaining the character of clay. Such a pond, becoming gradually filled, may be at this day a swamp, a peat-bed, or the site of glacial or alluvial drift, hiding its earlier character from view. Beneath such impermeable concave beds water derived from rain falling on the surface of the ground around their margin, may be prevented from draining away by other impervious beds lying in the way of its natural outlet. A driven well of no great depth, piercing such a concave bed of impervious clay or hard-pan, will permit the water to rise within it to the level of its natural outlet, just as an open well would also permit the same water to rise to the same height; and a depression of the water in or around the well, produced by drawing or pumping water out, will result in a convergent flow to

* The vastness of this natural reservoir may be inferred by comparing the area of the chalk with the channel of the Thames, which is greatly exaggerated in the drawing to render it visible.

restore the disturbed level. Such cases must be exceptional, but one of the cases I have described, within my own experience, must have had some such origin. Occasionally, true artesian wells are produced by sinking to moderate depths, not beyond the reach of driven wells. There are at Chicago several true artesian wells, not far from the shore of Lake Michigan, only from seven hundred to thirteen hundred feet in depth, from which water flows in large quantity above the surface of the ground, and rises, when the pipes are carried up so high, to a height of more than one hundred feet above the surface of the lake. This water must therefore be received from the clouds upon elevated land, yet there is said to be no land sufficiently elevated within a less distance than one hundred miles. The quantity of water is greatest when it is allowed to flow away near the surface of the ground, and diminishes steadily with increasing height until, at some height above the lake it would come to static equilibrium, and the flow would cease altogether. It is not easy to conceive the existence of conditions in permeable soil which can admit of such free and apparently unimpeded flow in obedience to hydrostatic pressure through one hundred miles of any soil. Nor is it easy to see what and where can be the natural obstruction to outflow into the lake, which causes this water to stand, when allowed to find its level more than one hundred feet higher than the surface of the lake.*

* *Artesian Wells, Chicago, Illinois. Proceedings of the Common Council,* 1870–71. *Page* 56.

Designation and Location of Wells.	Depth, in feet.	Diameter in inches.	Quantity in U. S. gallons discharged in 24 hours, by measurement.	Quantity in U. S. gallons in 24 hours, as estimated.	Head above Lake Michigan, in feet.
Artesian well, ...	700	4	–	300,000	105
Artesian well, No. 2, . .	700	$4\frac{7}{8}$	–	400,000	105
Stock yards, ...	1,300	$5\frac{1}{4}$	–	400,000	–
Stock yards, No. 2, . . .	1,200	$5\frac{1}{4}$	–	640,000	–
Glue factory, ...	1,185	$3\frac{5}{8}$	–	600,000	107
Bridewell, ...	1,135	$4\frac{1}{2}$	500,000	–	80
Riverside, ...	700	–	198,000	–	–
County house, ...	–	–	–	80,000	–
Irving park, ...	–	–	–	80,000	–
Rolling mill, ...	1,265	$3\frac{1}{4}$	–	170,000	–
N. W. Distillery, . . .	1,010	$3\frac{5}{8}$	500,000	–	100
Chicago Distillery Co., . .	–	–	80,000	–	–
Indiana St. Distillery, . .	1,310	$4\frac{1}{4}$	260,000	–	74
Lincoln park, ...	$1,178\frac{1}{2}$	$4\frac{1}{4}$	700,000	–	77
Mean in 24 hours, 350,571, .	–		2,238,000	2,670,000	–

These wells perfectly illustrate the principles we have found applicable to open wells and driven wells alike.

Since 1871, many additional wells have been sunk, and the quantity delivered at a given height, or the height at which a given quantity is delivered, has generally diminished. It will be observed that almost the largest quantity, estimated at 600,-000 gallons in 24 hours, equal to 25,000 U. S. gallons per hour; and at quite the greatest head above the Lake, 107 feet, was delivered by the smallest well, at the Glue Factory, only 3⅝ inches diameter.

This water is highly saline, as will appear by the following analysis by Dr. J. V. Z. Blaney. The water of Lake Michigan, which is comparatively pure, is placed in the first column, for comparison. The quantities in the tables are expressed in the number of grains in a gallon of water. The well water is considered unfit for domestic use; but it is nevertheless used to a certain extent, and is said to be eagerly relished by cattle at the stock yards. It is said to corrode iron pipe rapidly, so that "it appears that from seven months to four years is as long as any iron pipe will stand in connection with this water."

Dr. J. V. Z. Blaney's Analysis of Lake and Artesian Well Water.

SUBSTANCES.	Lake Michigan.	ARTESIAN WELLS.		
		Lincoln Park.	Indiana Street.	N. W. Distillery.
Sulphuric acid,	.3024	26.233	24.5736	23 1624
Carbonic acid,	2 5043	6 248	9.6948	6 1354
Chlorine,	.2083	7.092	6.9570	5.9220
Lime,	2.4796	10.593	11.4696	5.8524
Magnesia,	.6789	5.000	4.4100	4.9770
Soda,	–	9.352	4.5720	9.0813
Sodium,	.1350	4.592	13.1760	3 8367
Silicia,	.3512	.468	.5760	.7560
Iron and alumina,	.0756	–	–	.2880
Soda, combined with organic matter,	.0053	–	–	–
Organic matter,	1.2727	–	–	–
Total,	8.0133	69.578	75.4290	*63.0112

* *Sic.* There is some error in the last column, as the partial numbers do not make up the sum, which yet agrees with the sum in the next table, which adds up correctly. [J. C. H.]

Theoretical Combination of Substances.

SUBSTANCES.	Lake Michigan.	ARTESIAN WELLS.		
		Lincoln Park.	Indiana Street.	N. West Distillery.
Sulphate of lime,	.5141	25.727	27.8530	21.4992
Sulphate of soda,	–	19.663	14.5368	18.6660
Carbonate of lime,	4.0498	–		–
Chloride of sodium,	.3433	11.680	11.5300	9.7587
Carbonate of soda,	–	1.539	11.6740	1.5916
Carbonate of magnesia,	1.4013	10.501	9.2592	10.4517
Silicia,	.3512	.468	.5760	.7560
Iron of alumina,	.0756	traces.	traces.	.2880
Soda, combined with organic matter,	.0053	–		–
Organic matter,	1.2727	–	–	–
Total,	8.0133	69.578	75.4290	63.0112
Free carbonic acid, in cubic inches,	–	8.387	6.062	6.760

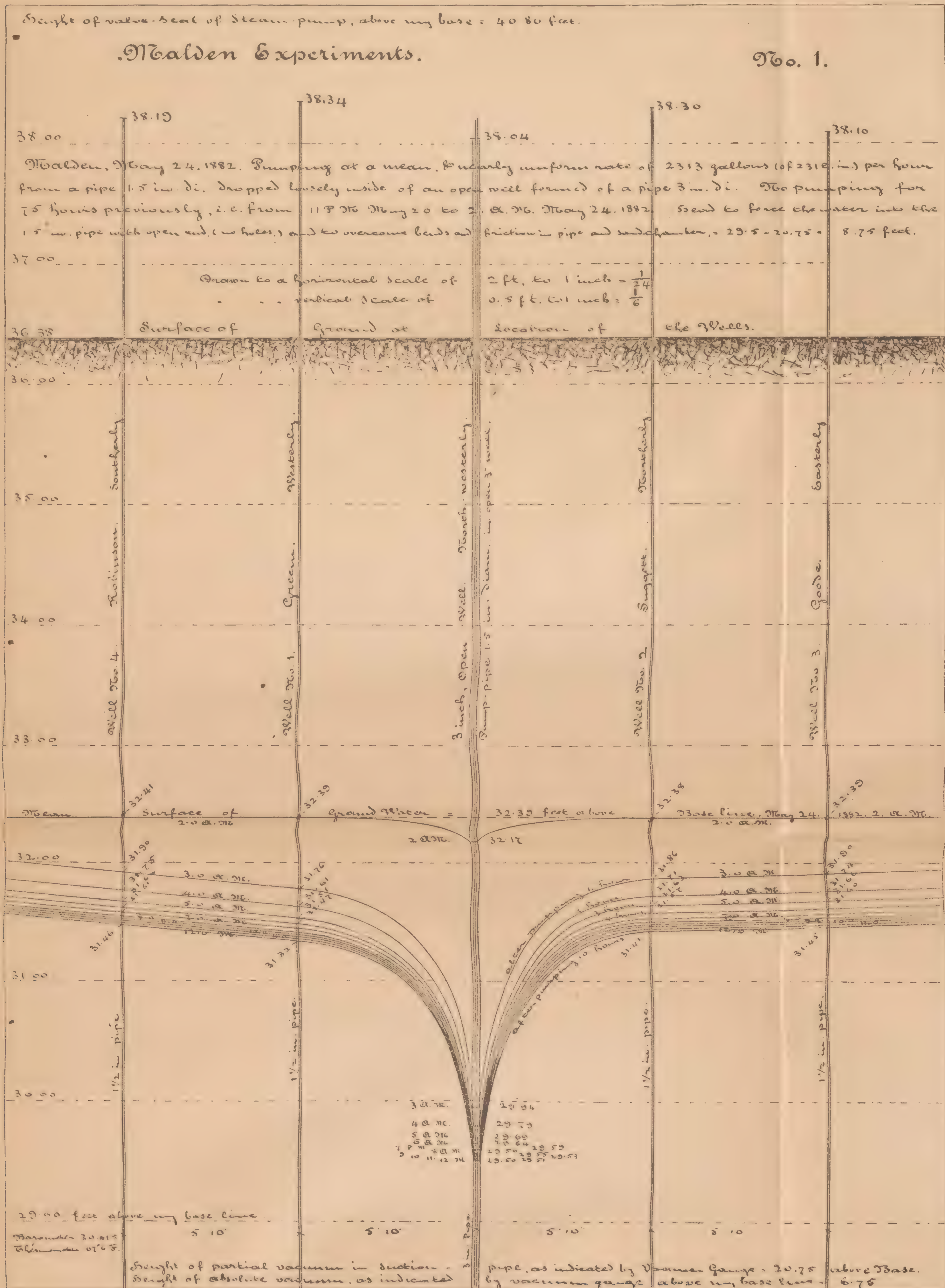
[Proceedings of common council, Chicago, 1870-71, p. 55.] J. C. H.

When no water is drawn from them, and they are allowed a period of repose, the water finds its level under an equal weight of atmosphere everywhere — at the well, and at the remote source — and all flow towards the well is arrested. When, on the other hand, water is allowed to flow away at a lower level, the water-surface is depressed, and a convergent flow takes place, proportioned to the slope caused by the depressed surface. If, by means of a pump attached to the pipe, a part of the atmospheric weight be lifted off, producing the equivalent of a steeper slope, the quantity of water will be proportionately increased, precisely as if by means of a pump with its suction pipe inserted freely in the tube of the well, a quickened flow and a depressed water surface would be produced.

Indeed, the principles are of universal application — wherever water moves, horizontally, in the soil, it moves by the impelling force of gravity, against the opposing force of interstitial friction; and in given conditions of soil, its flow can be accelerated in no other way than by increasing the slope.

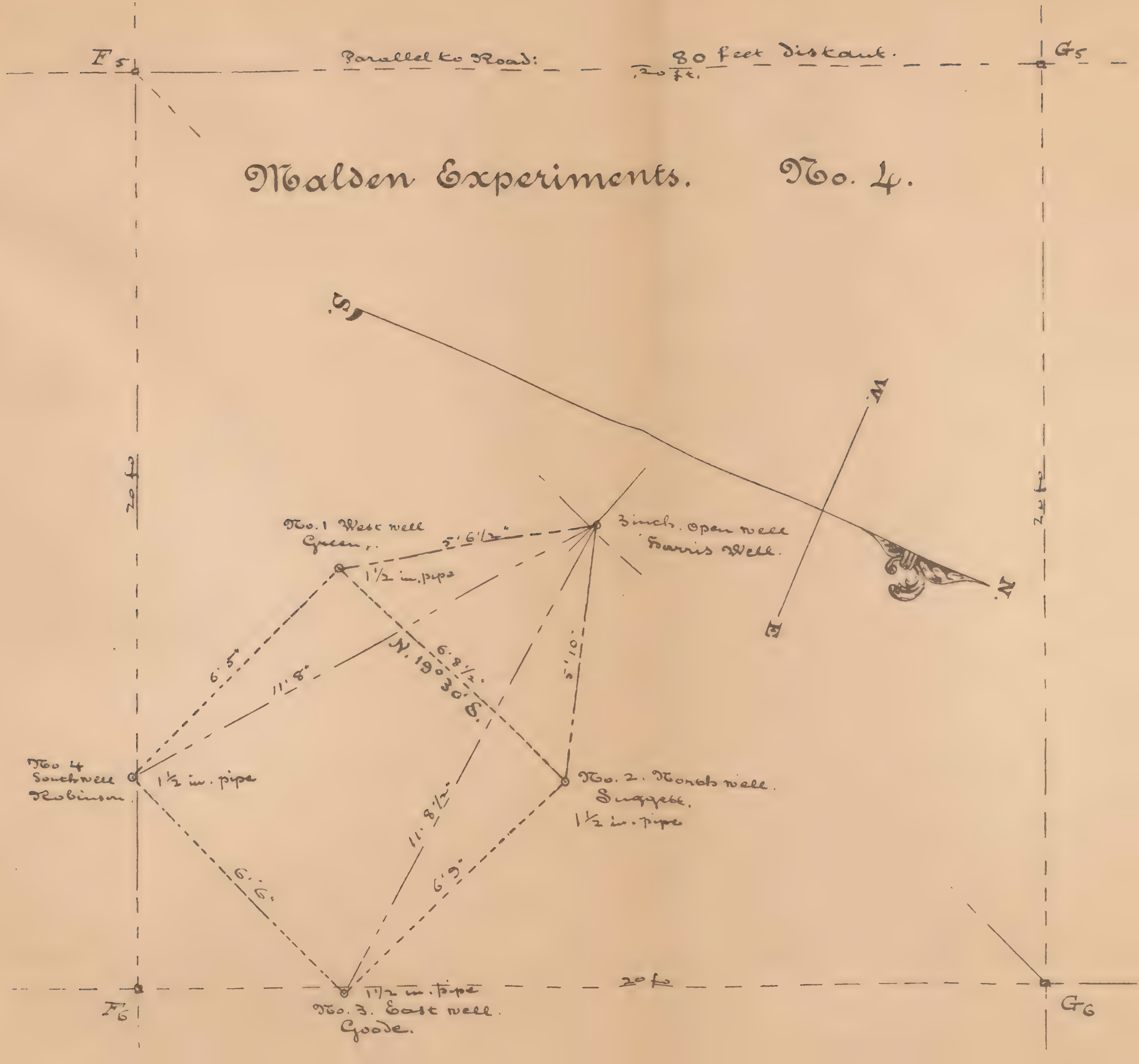
The accompanying diagram, marked "Malden Experiments," Fig. 1, embodying the results of 10 hours continuous pumping out of a tubular well composed of 3-inch gas-pipe sunk loosely into the ground about 30 feet, open at the lower end, and having no holes drilled in the lower portion of its length. The suction-pipe was of 1½-inch gas pipe, open at its lower end, and without perforations, dropped loosely into the 3-inch well-lining, and so supported as to leave the surface of water in the latter, outside of the suction-pipe, constantly exposed to the full weight of the atmosphere. A steam-pump was used, with a sand-chamber between it and the upper end of the suction-pipe; and the speed of this pump was so regulated as to deliver all the water which could flow into the chamber of the pump, keeping it completely filled, to avoid the shocks resulting from a higher speed than the water could follow.

The four wells in which measurements were taken, were located as seen on sheet "Malden Experiments," No. 4. They were all of 1½-inch gas-pipe, inserted about 30 feet in the ground, and free from soil within.



Height of valve-seat of Steam-pump, above my base = 40.80 feet.
Malden Experiments.
No. 1.
38.19
38.34
38.04
38.30
38.10
38.00
Malden, May 24. 1882. Pumping at a mean, & nearly uniform rate of 2313 gallons (of 231 c. in.) per hour from a pipe 1.5 in. di. dropped loosely inside of an open well formed of a pipe 3 in. di. No pumping for 75 hours previously, i.e. from 11 P.M. May 20 to 2. A.M. May 24. 1882. Head to force the water into the 1.5 in. pipe with open end (no holes) and to overcome bends and friction in pipe and sandchamber = 29.5 - 20.75 = 8.75 feet.
37.00
Drawn to a horizontal scale of 2 ft. to 1 inch = 1/24
vertical scale of 0.5 ft. to 1 inch = 1/6
36.58
Surface of Ground at Location of the Wells.
36.00
35.00
34.00
33.00
Well No. 4. Robinson. Southerly.
Well No. 1. Green. Westerly.
3 inch, Open Well. North-westerly.
Pump-pipe 1.5 in. diam. in open 3" well.
Well No. 2. Suggett. Northerly.
Well No. 3. Goode. Easterly.
32.41
32.39
32.38
32.39
Mean Surface of Ground Water = 32.39 feet above Base line. May 24. 1882. 2. A.M.
2.0 A.M.
2 A.M.
32.17
32.00
31.90
31.76
31.86
31.90
3.0 A.M.
4.0 A.M.
5.0 A.M.
12.0 M.
31.46
31.32
31.41
31.45
after pumping 1 hour
after pumping 10 hours
31.00
30.00
1½ in. pipe
3 A.M.
4 A.M.
5 A.M.
6 A.M.
8 A.M.
10 11 12 M.
29.94
29.79
29.69
29.64
29.59
29.56
29.55
29.53
29.50
29.51
29.00 feet above my base line.
3 in. Pipe
5.10
Barometer 30.015
Thermometer 67° F.
Height of partial vacuum in suction-pipe, as indicated by Vacuum Gauge = 20.75 above Base.
Height of absolute vacuum, as indicated by vacuum gauge above my base line = 6.75

Malden Experiments. No. 4.



The slight depression at the 3-inch open well, 0.22 feet (32.39 — 32.17) at the beginning of the experiment, at 2 o'clock A. M., was caused by trying the pump just before the measurements were made for starting. The subjoined table, table I., shows in feet and decimals of a foot the measured height of the water-surface in each of the five wells above an assumed reference plane, 1st, at starting at 2 o'clock A. M., and 2d, after continuous pumping during one hour, at 3 o'clock A. M.; and also, by the differences of these two sets of heights, the amount of depression produced by pumping during this first hour, at each well.

TABLE I.

TIME.	1½ inch, No. 4.	1½ inch, No. 1.	3 inch, open well.	1½ inch, No. 2.	1½ inch, No. 3.
2 A.M.,	32.41	32.39	32.17	32.38	32.39
3 A.M.,	31.90	31.76	29 94	31.86	31.90
Dif.,	.51	.63	2.23	.52	.49

A slope from all directions towards the 3-inch well has now been established, just steep enough to supply the quantity of water which the suction-pipe and pump can properly discharge; but the diameter of the circle drawn upon, although large, is not large enough to supply this quantity of water continuously.

We shall therefore find, as the result of continued pumping, that the slope, although constant as to steepness, is drawn down continually lower, but with diminishing rapidity, until a regimen is attained which just supplies the demands of the pump by the natural flow of the intercepted sheet of under-ground water, after which both the steepness and the height of the slope remain constant until, indeed, rains or other causes alter the conditions. The subjoined tables show the progress of this epression of a slope of uniform steepness.

Table II.

Lowering of the Surface of the Ground-water after Two Hours Continuous Pumping.

Time.	1½ inch, No. 4.	1½ inch, No. 1.	3 inch, open well.	1½ inch, No. 2.	1½ inch, No. 3.
A.M., ...	32.41	32.39	32.17	32.38	32.39
A.M., ...	31.75	31.61	29.79	31.71	31.74
2d dif., ...	.66	.78	2.38	.67	.65
1st dif., ...	.51	.63	2.23	.52	.49
3 to 4, ...	.15	.15	.15	.15	.16

Table III.

Lowering of the Surface of the Ground-water after Three Hours Continuous Pumping.

2 A.M., ...	32.41	32.39	32.17	32.38	32.39
5 A.M., ...	31.66	31.51	29.69	31.63	31 66
3d dif., ...	.75	.88	2.48	.75	.73
2d dif., ...	.66	.78	2.38	.67	.65
4 to 5, ...	.09	10	.10	.08	.08

Table IV.

Lowering of the Surface of the Ground-water after Four Hours Continuous Pumping.

2 A.M., ...	32.41	32.39	32.17	32 38	32.39
6 A.M., ...	31.61	31.47	29.64	31.57	31.60
4th dif., ...	.80	.92	2.53	.81	.79
3d dif., ...	.75	.88	2.48	.75	.73
5 to 6, ...	.05	.04	.05	.06	6.0

Table V.

Lowering of the Surface of the Ground-water after Ten Hours Continuous Pumping.

2 A.M., ...	32.41	32.39	32.17	32.38	32.39
12 M., ...	31.46	31.32	29.50	31.41	31.45
5th dif., ...	.95	1.07	2.67	.97	.94
4th dif., ...	.80	.92	2.53	.81	.79
6 to 12, ...	.15	.15	.14	.16	.15

In the subjoined table (table VI.), the depression produced at each well by each hour's pumping, (brought from tables I., II., III. and IV., for the first four hours, from sheet "Malden Experiments," "No. 1," so far as relates to the central, 3-inch well, for the remaining six hours, and interpolated, in the four 1½-inch wells, for the last six hours — the interpolated figures being in italics) — may be seen at a glance.

TABLE VI.

Effect of Pumping Hour by Hour: Feet.

No.	Time.	1½ inch, No. 4.	1½ inch, No. 1.	3 inch, open well.	1½ inch, No. 2.	1½ inch, No. 3.
1, . . .	2 to 3	.51	.63	2.23	.52	.49
2, . . .	3 to 4	.15	.15	.15	.15	.16
3, . . .	4 to 5	.09	.10	.10	.08	.08
4, . . .	5 to 6	.05	.04	.05	.06	.06
5, . . .	6 to 7	*.05*	*.05*	*.05*	*.05*	*.05*
6, . . .	7 to 8	*.04*	*.04*	*.03*	*.04*	*.04*
7, . . .	8 to 9	*.03*	*.03*	*.01*	*.03*	*.03*
8, . . .	9 to 10	*.02*	*.02*	*.02*	*.02*	*.02*
9, . . .	10 to 11	*.01*	*.01*	*.02*	*.01*	*.01*
10, . . .	11 to 12	*.00*	*.00*	*.01*	*.01*	*.00*
	2 to 12 10 hours	.95	1.07	2.67	.97	.94

It will be seen, by studying the foregoing tables, that of the whole depression produced in the four 1½-inch wells by pumping continuously from the central 3-inch well during 10 hours, 55 per cent. was produced in the first hour; and that of the whole depression produced at the 3-inch open well by 10 hours continuous pumping from that well, 85 per cent. was produced in the first hour. Further, that as much depression was produced in all the wells during the second hour (from 3 to 4 o'clock), as during the six hours from 6 to 12 o'clock. It will also plainly appear that the first hour's pumping established a normal slope corresponding to the quantity of water delivered by the pump, which was 2,313 gallons (of 231 cubic inches) per hour, equal to 38.55 gallons per minute, and to 2.57 quarts (0.6425 gallon) per second, — the slope required in this soil to cause such a quantity of water to flow, in obedience to gravity alone convergently

towards and up to the suction pipe of the pump which produced and maintained the depression *at* the well and the slope *towards* it. It is no less clear that such a normal slope, when once established, remained unchanged during the whole period of subsequent pumping, as will appear by inspection of the lower line of differences in tables II., III., IV. and V.

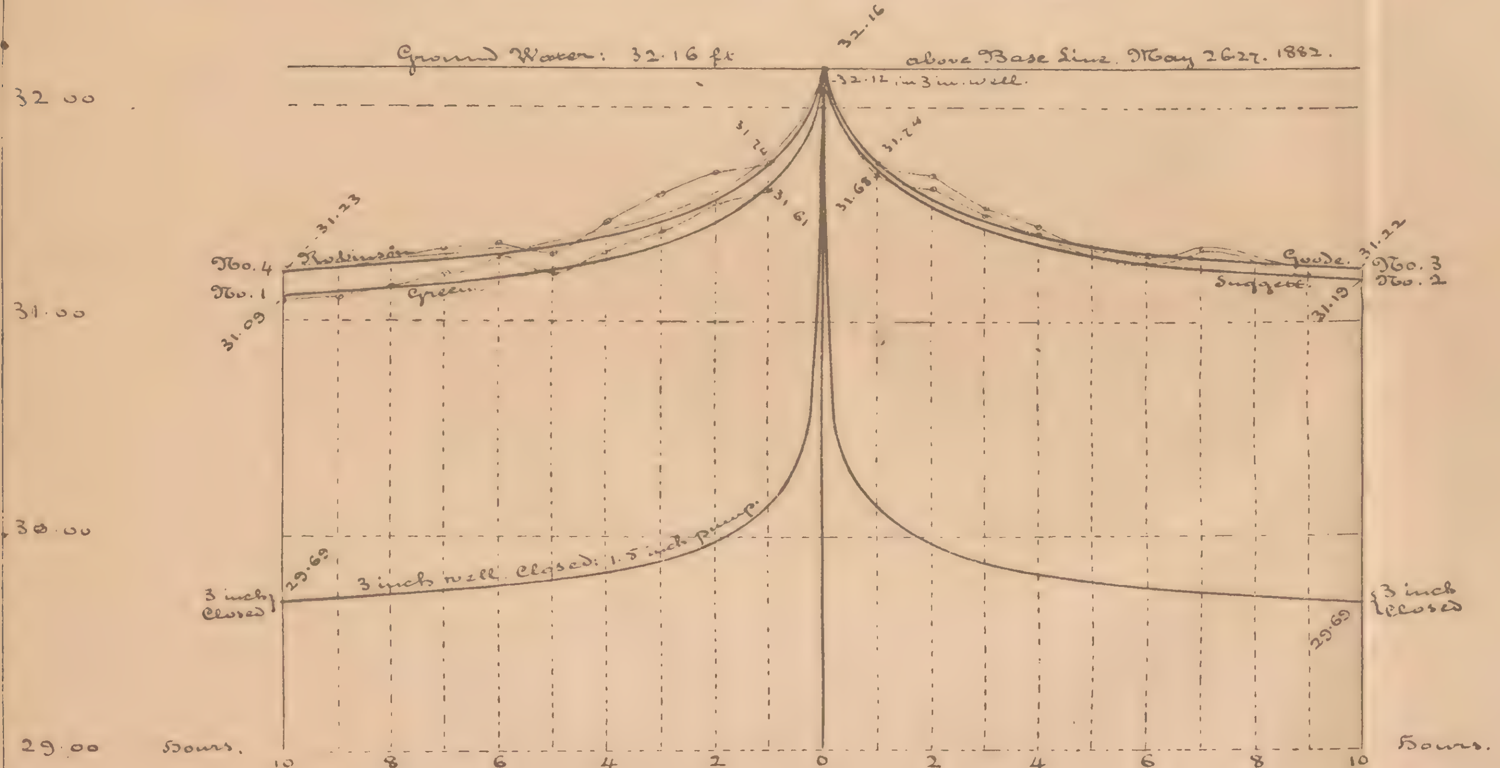
The progressive lowering of the slopes at each of the five wells, hour by hour as pumping went on, is clearly shown in the lower diagram on the sheet "Malden Experiments, No. 2," in which the curves for two of the $1\frac{1}{2}$-inch wells, No. 2 and No. 3, are placed at the right-hand of the central axis, and the other two, No. 4 and No. 1, are placed at the left-hand of the same axis; while the single curve for the central 3-inch open well is duplicated, for symmetry, and for direct comparison with the others.

The form of these curves shows the progressive establishment of a permanent regimen, according to which the draught of water by the pump and the convergent inflow by gravity would be in equilibrium; while the parallelism of the curves, after the first hour, shows the persistence of the slope required by this rate of inflow. The difference in the steepness of the slope, radially, between well No. 2 and well No. 3, on the one hand (0.04 feet in 5.83 feet), and between well No. 1 and well No. 4, on the other hand, (0.14 feet 5.83 feet), indicates some diversity in the retentiveness of the soil about the 3-inch well. The slope above mentioned certainly did not continue unchanged outward to the limit of the inflow, but approached gradually nearer to the horizontal. The mean of the two slopes above mentioned is 0.09 feet in 5.83 feet, equal to 0.01543 feet in 1 foot horizontal. The mean of the slope outward from well No. 4 and well No. 3. to the limit of their influence, probably did not exceed one-third of this, say 0.005 feet in 1 foot horizontal, or 1 foot in 200 feet. Then, the depression being 0.95 feet at No. 4, and 0.04 feet at No. 1, say 0.945, we should have as the horizontal distance from which water was concentrated, by gravity, towards the depressed surface of water at wells No. 1 and No. 4, $\frac{0.945}{.005} = 185$ feet, to which add the distance in a right line from each of these wells to the central 3-inch well, say about 15 feet, and we have a

Malden Experiments.

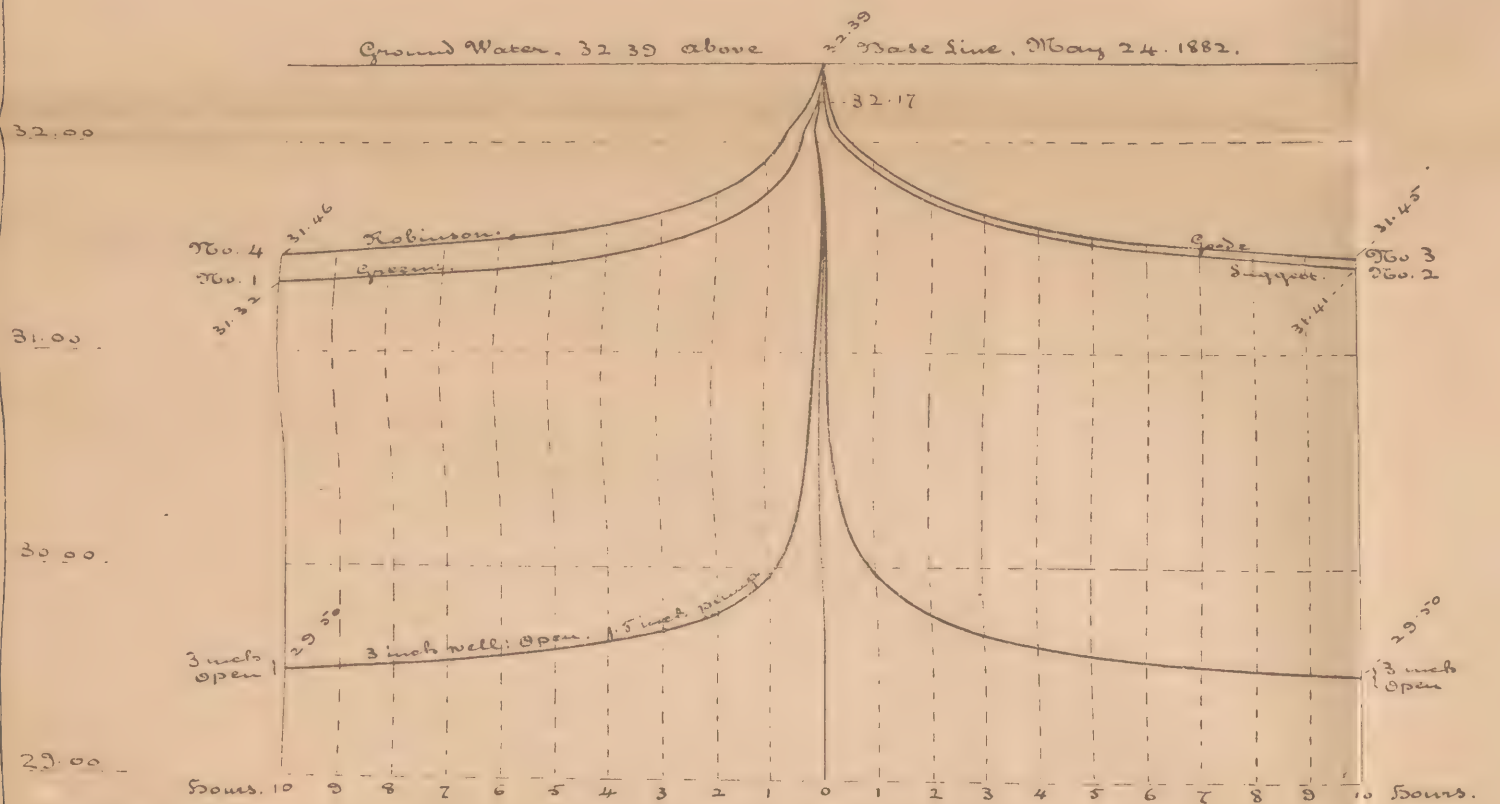
No. 2.

Malden, May 26-27. Pumping at a mean rate of 2118 Gallons per hour, (maximum = 2334, minimum = 1683 gals. per hour.) from a 1.5 inch pipe screwed into an air-tight cap screwed on top of the 3 inch pipe, which ceases to be an Open well, and becomes a Closed well. No pumping for 17 hours previously, from 3 P.M. May 25, to 9.0 A.M. May 26



Barometer = 30.009 in
Thermometer = 69.4 F

Height of vac. of 8.5 lb per sq. in. = 21.16 ft. above base: Full vac. at 6.75 above base. –



Barometer = 30.015 in.
Thermometer 67.6 F

Height of partial vacuum = 20.75 above base; Full vacuum = 6.75 above base = 40.80 - 34.05

radius of about 200 feet for the sink, or crater, into which water flowed from all sides. In the location in question, a ledge of granite rock on one side within a less distance than 200 feet, interfered with the symmetry of this crater, and its symmetry was doubtless otherwise disturbed by diversity of soil. The computation can only apply to homogeneous soil and uniform conditions. Effects altogether similar were obtained by pumping continuously for a like period of ten hours from this same central 3-inch well when fitted with a cap, closing the space at its upper end around the 1½-inch suction pipe, as will be seen upon the upper diagram of the last above mentioned sheet, "Malden Experiments, No. 2," constructed precisely in the manner already explained with reference to the lower diagram of that sheet. Some faint lines on the upper diagram show the disturbing effect of rain which fell during the ten hours of the experiment.

Pumping in turn continuously for a like period of ten hours from each one of the 1½-inch wells, in like manner presented the same results and produced effects substantially similar, the chief difference being a slight variation in the quantity of water — the largest quantity, but only a little the largest, being obtainable from the Goode well, and the next largest quantity from the 3-inch well when it was open at the top to the air.

The quantity of water obtained from the several wells respectively, when all were operated, as nearly as possible, in the same manner, is given in the subjoined table.

TABLE VII.

Yield of Water — Gallons per Hour.

No. 1. Green.	No. 2. Suggett.	No. 3 Goode.	No. 4. Robinson.	3 inch. Open.	3 inch. Closed.
1,779	2,153	2,458	2,010	2,313	2,118

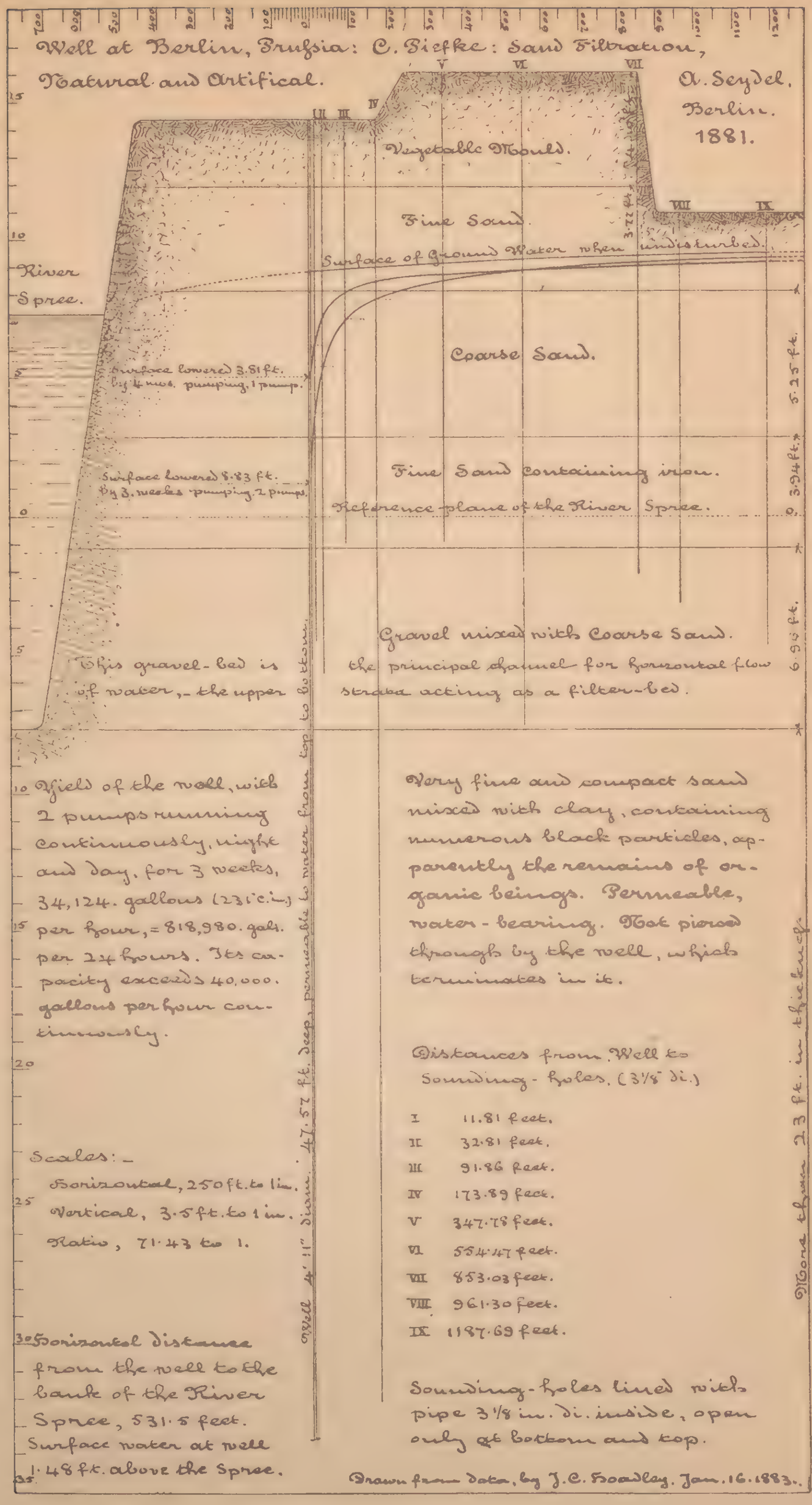
A little the most water was obtained from well No. 3 — formed of a tube of 1½-inch gas-pipe, open at the lower end, without perforations, inserted loosely in a hole prepared for it, according to the manner described and shown by John

Goode in his letters patent of Great Britain No. 4,838 of the year 1823. Taking that quantity, 2,458 gallons per hour, as a standard of comparison for all the others, and calling that 100, we have :—

Yield of the Goode well, No. 3,	100
" " Suggett well, No. 2,	88
" " Robinson well, No. 4,	82
" " Green well, No. 1,	72
" " 3-inch well, open,	94
" " 3-inch well, closed,	86

Some difference in the permeability of the soil may have caused a part of the above differences, which, after all, are too slight to lay much stress on.

The local depression and resulting convergent inflow of surrounding water produced by pumping or otherwise drawing water out of a well, and the curved contour of the water surface in radial, vertical section, convex upward, are found everywhere upon observation and careful measurement, and being in strict accordance with well-established natural laws, may be considered of universal prevalence. A striking example is seen on the sectional diagram facing p. 32 showing the effect of long-continued, uninterrupted pumping from a well at Berlin, Prussia. The capacity of this well was very large, no less than 40,000 gallons (of 231 cubic inches) having been drawn from it every hour of the day and night for months at a time. The water was used for condensing the steam of a compound steam-engine for the water-works at the Stralauer Thor, the demand requiring the use sometimes of one, sometimes of both, of two pumps set in the well. The well shaft is 4 feet 11 inches (1.5 metres) in diameter, and 47.57 feet deep, and its lining is permeable to water for its entire depth. It is located only 531.5 feet from the banks of the river Spree, into which the ground water naturally drains, with a curved slope, as indicated on the diagram by a line partly dotted, and the soil, composed of several level strata of sand and gravel, extends with great uniformity to a considerable distance from the river, certainly more than a mile. Continuous pumping during four months, with one pump only, produced a depression of the water surface of only 3.81 feet below the natural surface of ground water at the well; but the slope at 1,187.69



Well at Berlin, Prussia: C. Piefke: Sand Filtration, Natural and Artifical.
A. Seydel. Berlin. 1881.
I II III IV V VI VII VIII IX
Vegetable Mould.
Fine Sand.
3.77 ft.
Surface of Ground Water when undisturbed.
River Spree.
Coarse Sand.
Surface lowered 3.81 ft. by 4 hrs. pumping, 1 pump.
5.25 ft.
Fine Sand containing iron.
Surface lowered 8.83 ft. by 3 weeks pumping, 2 pumps.
3.94 ft.
Reference plane of the River Spree.
Gravel mixed with Coarse Sand.
This gravel-bed is the principal channel for horizontal flow of water, — the upper strata acting as a filter-bed.
6.96 ft.
Yield of the well, with 2 pumps running continuously, night and day, for 3 weeks, 34,124. gallons (231 c.in.) per hour, = 818,980. gals. per 24 hours. Its capacity exceeds 40,000. gallons per hour continuously.
Very fine and compact sand mixed with clay, containing numerous black particles, apparently the remains of organic beings. Permeable, water-bearing. Not pierced through by the well, which terminates in it.
Well 4' 11" diam. 47.57 ft. deep, permeable to water from top to bottom.
More than 23 ft. in thickness.
Distances from Well to Sounding-holes. (3 1/8" di.)
I 11.81 feet.
II 32.81 feet.
III 91.86 feet.
IV 173.89 feet.
V 347.78 feet.
VI 554.47 feet.
VII 853.03 feet.
VIII 961.30 feet.
IX 1187.69 feet.
Scales: —
Horizontal, 250 ft. to 1 in.
Vertical, 3.5 ft. to 1 in.
Ratio, 71.43 to 1.
Horizontal distance from the well to the bank of the River Spree, 531.5 feet.
Surface water at well 1.48 ft. above the Spree.
Sounding-holes lined with pipe 3 1/8 in. di. inside, open only at bottom and top.
Drawn from data, by J. C. Hoadley. Jan. 16. 1883.

feet distance was such as to indicate a convergent flow from a distance of more than 3,000 feet. Again, continuous pumping with both pumps, during a period of only three weeks, produced a depression of 8.83 feet, but a steeper slope, a smaller depression at well IX., 1,187.69 feet distance, and a smaller radius of convergent flow, doubtless because the remote effect had not made itself fully felt in so short a time. It is obvious that all over the wide area drained by this well, all soluble substances upon the surface of the ground must be dissolved by the rains, and sink through the soil straight down to the water, and join the water under ground in its stealthy flow to and into the well.

It may be worth while to remark that all the water obtained from this well was satisfactorily proved by its physical and chemical qualities to have come by natural filtration from the superior strata, above the level of the depressed water-surface in the well; none came up from below. This is in accordance with well-established natural laws, in the absence of conditions favoring the construction of artesian wells. Another well at Berlin, connected also with the city water-works, yields a still larger quantity of water, and draws its supply from a tributary area of 5,000 metres (3.1 miles) radius, embracing 30 square miles.

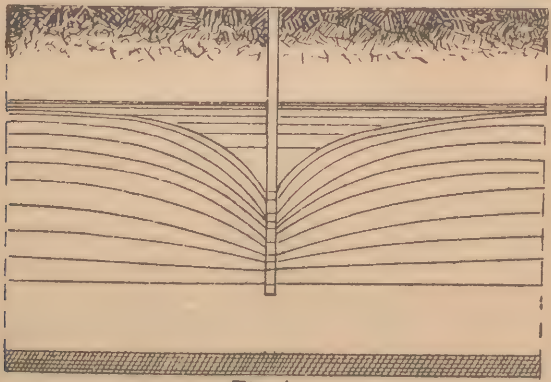


Fig. 1

Figure I. illustrates the convergent flow towards a well on a vertical section at right angles to the general direction of the underground flow. As usual, the vertical scale is greatly exaggerated, relatively to the horizontal scale,

for the sake of clearness. This exaggeration is necessary in order to render conspicuous at a glance relations which on the natural scale can be determined only by close observation and careful measurement. The hatching near the top, indicates the surface of the ground. The shaded space at the bottom indicates an impermeable stratum. The level lines indicate the natural position of undisturbed ground-water; the curved lines show the effect of a convergent flow towards the depressed surface of water in a well from which water is continuously drawn.

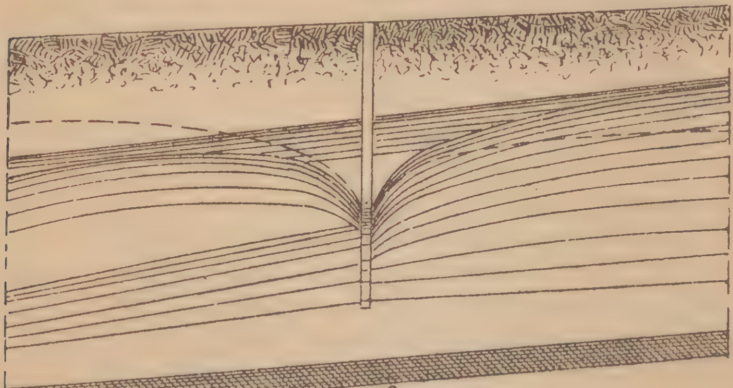


Fig. 2

Figure II., in like manner, indicates the condition of things seen in fig. I., but on a vertical plane parallel to the general direction of the underground water, and therefore at right angles with the course of the plane of fig. I.

It is obvious that the water below the lowered surface in the well, on the down-stream side, must flow away from the well, as seen in fig. II.

Figure III. illustrates an occurrence not very uncommon, —two strata of some impermeable material, clay, shale, or hard rock—with permeable strata—sand or gravel—overlying each and producing two subterranean streams, quite independent as far as the dividing septum extends. A well sunk into the upper water-bearing stratum only, will produce by pumping an effect shown in the upper part of fig. III. Driven through the upper impermeable stratum and not into the water of the lower water-bearing stratum, it would, if its walls were permeable, drain water away

Profile

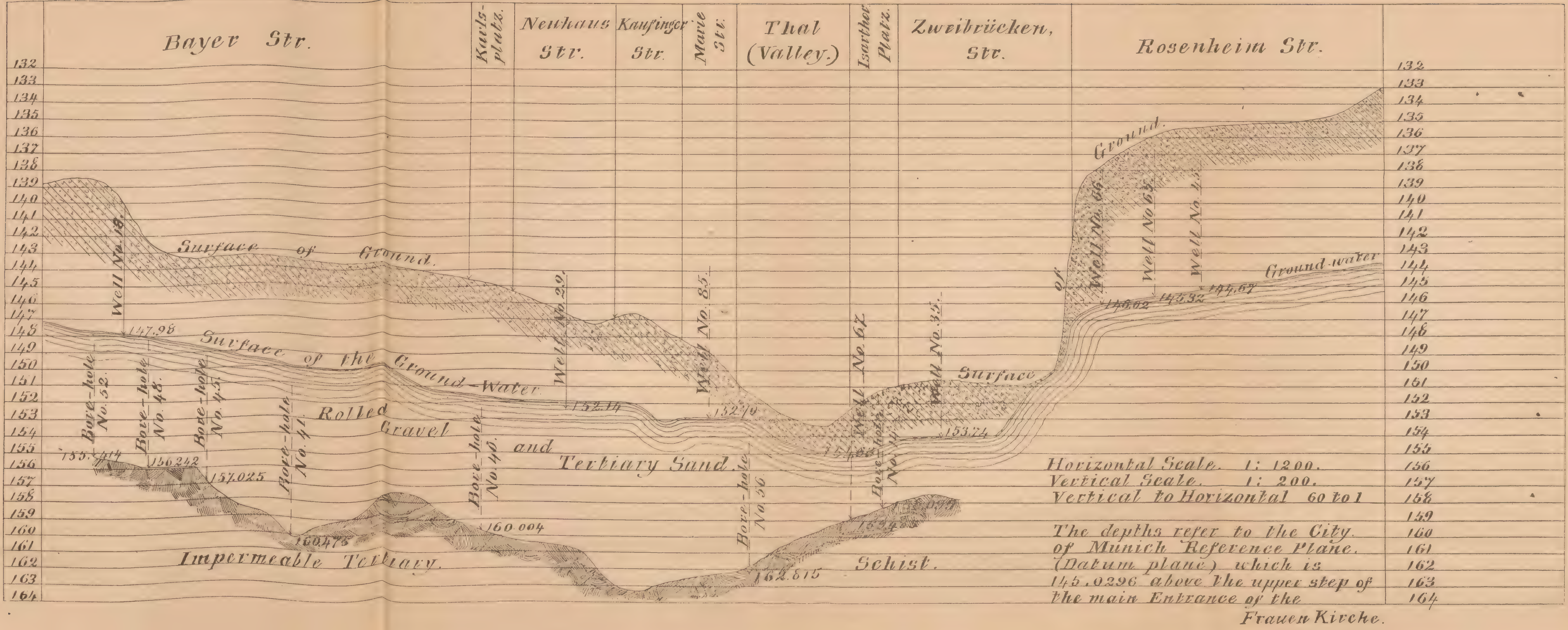
Of the Elevation of the Impermeable Tertiary Schists.

And the Ground-water level. Middle of Aug. 1875.

Direction. Northwest-East.

Fig. IV.

Middle of August, 1875. - Direction. West - East. Fig. V.



Profile.

Of the Elevation of the impermeable tertiary Schists And the Ground-water level, Middle of August, 1875.

Direction, North-west, South-east.

Fig. VI.

Middle of August – 1875 — Direction. West - South-east. Fig. VII.

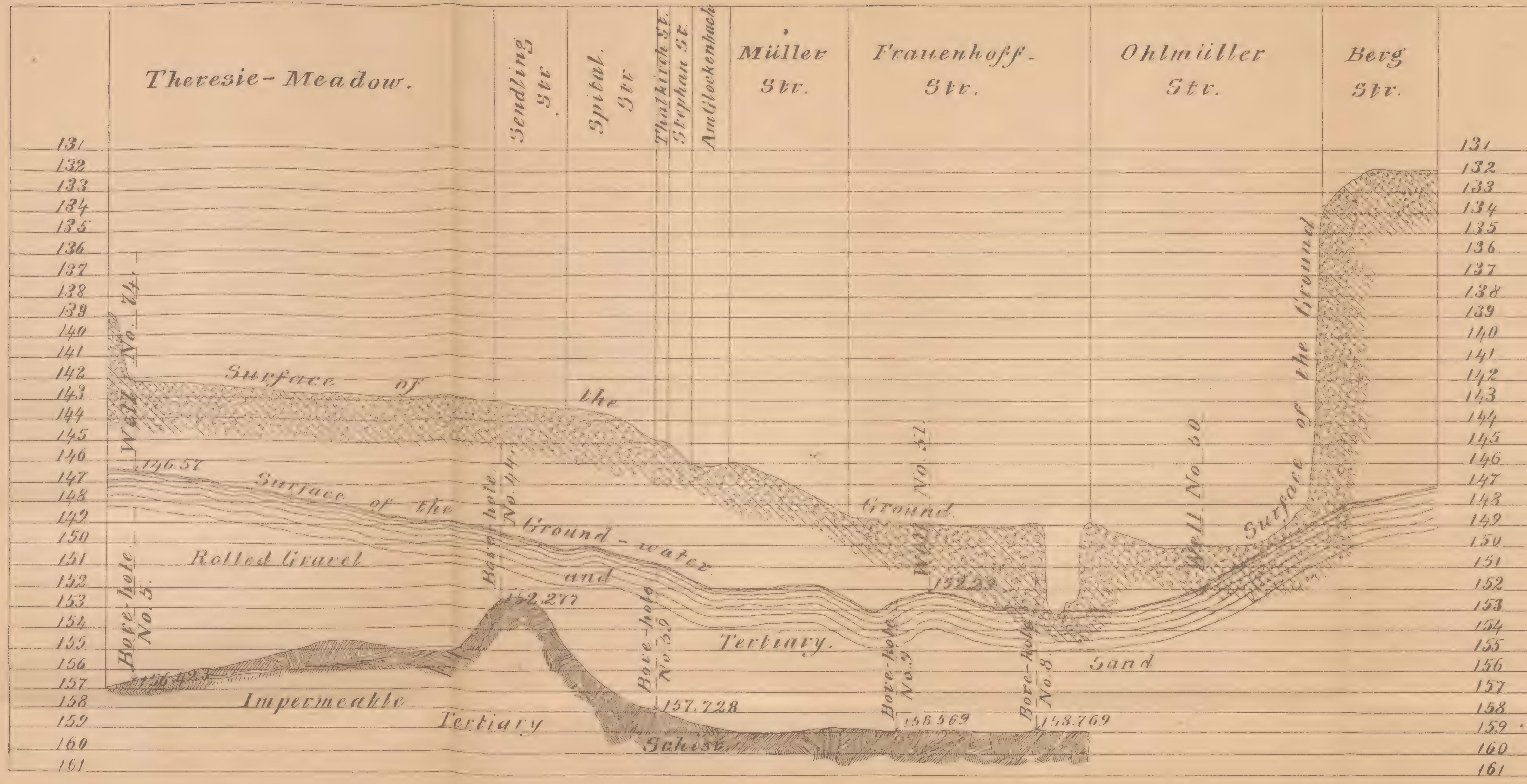


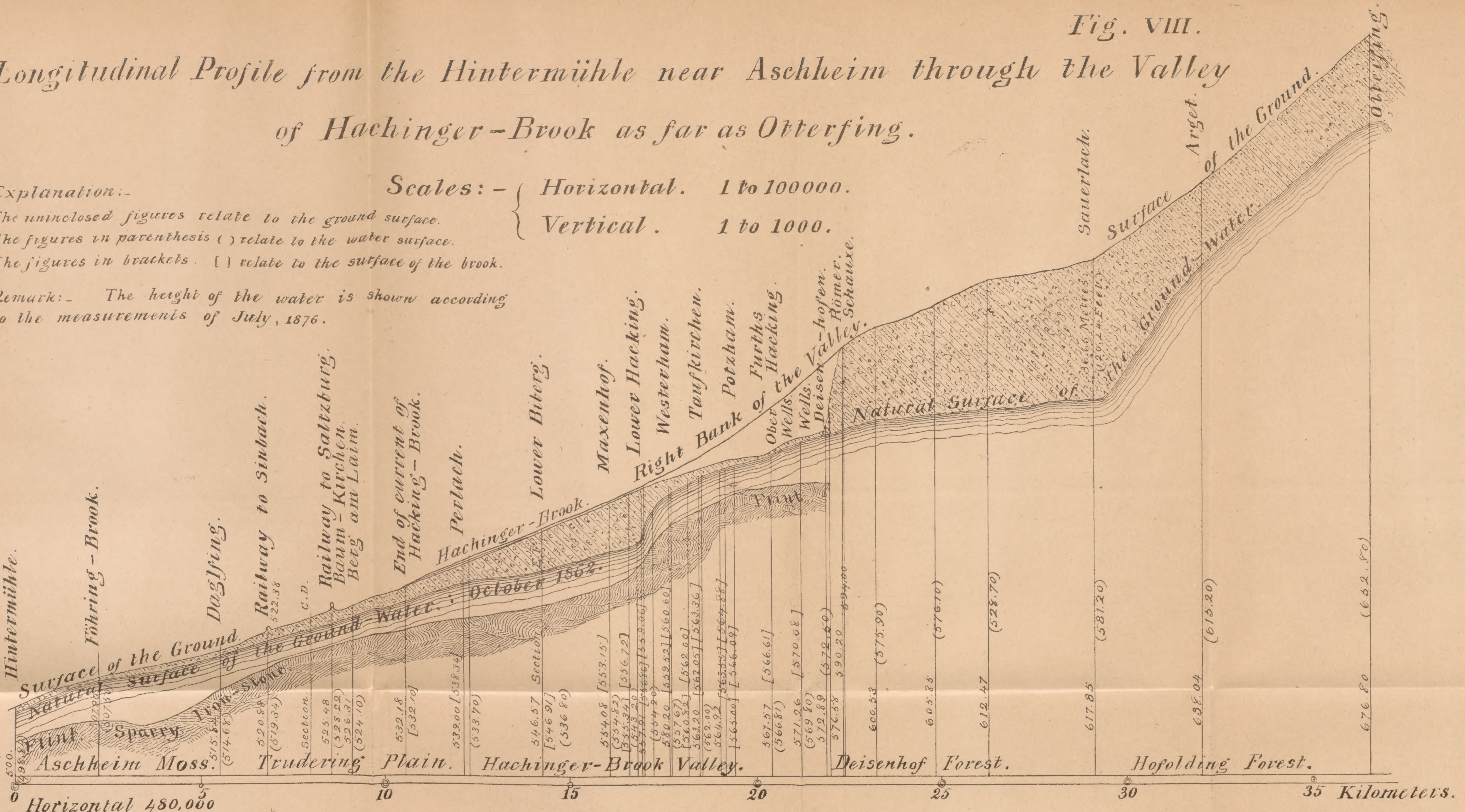
Fig. VIII.

Longitudinal Profile from the Hintermühle near Aschheim through the Valley of Hachinger-Brook as far as Otterfing.

Explanation:-
The uninclosed figures relate to the ground surface.
The figures in parenthesis ( ) relate to the water surface.
The figures in brackets [ ] relate to the surface of the brook.

Remark:- The height of the water is shown according to the measurements of July, 1876.

Scales:- Horizontal. 1 to 100000.
Vertical. 1 to 1000.



Wasserversorgung der Stadt Munchen. A. Thiem.

from the upper stream into the stream below. Sunk into the lower water-bearing stratum and impermeable all the way up to the top, it would produce by pumping the inflow indicated in the lower part of fig III.

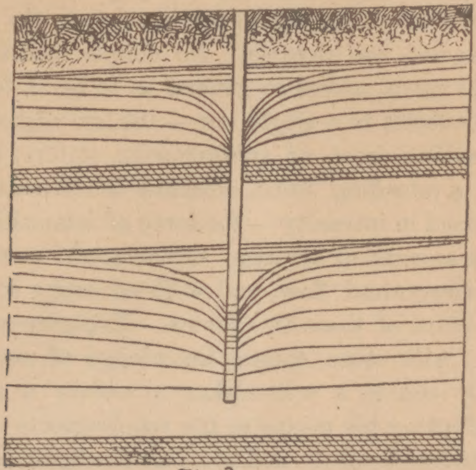


Fig. 3

Figures IV., V., VI., VII. and VIII. show the mutual relations of the upper surface of the ground, the surface of the ground-water, and the upper surface of the underlying impermeable strata, over a large area in the city of Munich, Bavaria, by actual determination, in the month of August of the year 1875. In some places the water flows quite near the surface of the ground; in other places, at a great depth below the surface. It stands in deep pools in parts of the impenetrable strata beneath it, and flows in a thin sheet over other parts, as over a weir — notably at bore-hole No. 3, fig. VI., and at bore-hole No. 36, fig. IV. Sometimes it must find an outlet in some direction other than that of the section-plane. The water at bore-hole No. 28, fig. VI., cannot reach the channel divided by an island at the right-hand, by direct flow in the direction of this section-plane, but must flow into it at some point farther down-stream; and other like cases will be noticed.

Figure VIII. illustrates the case often met, of shallow wells near the summit of a hill, and much deeper wells in lower ground at no great distance. Near the sum-

Corey's Hill, in Brookline, there is an unfailing well in which the water stands only ten or twelve feet below the surface of a gentle slope. Only a few rods distant there is a well on ground 200 feet lower, in which the water stands thirty-five to forty feet below the surface of a plain.

The conditions under which water exists in the ground are endlessly varied and diverse. No simple classification can embrace all cases, unless so general as to be of little value; but all are subject to a single law — the law of gravitation — the sole moving force of subterranean waters, and all are subject to a retarding force, constant in character, but extremely varied in intensity — the force of interstitial friction. All the phenomena of springs, subterranean streams, wide, diffused underground flow, and wells of every kind depend on the resultant of these two forces. Experience and common sense, with some special knowledge of each locality, will usually enable a well-sinker to obtain a satisfactory well, by adapting his means to the requirements of the case, with reasonable certainty and at a cost susceptible of calculation to a reasonable degree of approximation, in advance. The silly superstition of the divining rod, which shares with ancient astrology and modern spiritism, the invincible credulity of a certain class of minds, is generally harmless, as there is no *less* likelihood of finding water where the witch-hazel points (!) than elsewhere.

When it is considered that water is an almost universal solvent, and that the earth, alike upon its surface and in its depths, abounds in soluble substances, many of them deleterious, it appears remarkable that well-water is not, in general, more polluted than it is found to be.

But it is impossible to impress too strongly the importance of keeping at a great distance from every well used for domestic purposes, every source of contamination.